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THE
JOURNAL OF GEOLOGY

MAY-JUNE, 1907

THE METAMORPHIC CYCLE

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Katamorphism.—Igneous rocks, when affected by meteoric agencies at and below the weathering surface, tend to become adjusted to their new environment in such a manner that their constituents become distributed as follows:

- Original igneous and crystalline rocks
  - Material removed
    - Carried as solids
      - Mechanical sediments—
        - Shales
        - Sandstones
        - Conglomerates, etc.
    - Carried in solution
      - Chemical sediments—
        - Limestone, etc.
      - Cementing materials
      - Vein-filling materials
      - Mineral matter of the sea
  - Material remaining.............
    - Weathered rock
    - Residual clays and soils

Fully 97 per cent. of the end-products are sediments included under the general names of shales, sandstones, and limestones. Arkoses, graywackes, conglomerates, etc., containing original complex silicates, may be regarded as intermediate stages of alteration, and may thus be disregarded in a consideration of ultimate products. Of these the shales are by far the dominant sediments, as shown by field observation, by measurement of river loads, and by calculations of the relative proportions of the three sediments necessary most nearly to approximate the composition of the parent rocks. The last method, which is well based, puts the average percentage of shales, derived from the average igneous or crystalline rock, as high as 79 per cent., the sandstones constituting 12 per cent., and the limestones 9 per cent. of the total of these three sediments.[1] Averages of sections made from field observations give uniformly a lower percentage of shales and higher percentage of limestone. An average of twenty-one sections from different parts of the United States shows 30 per cent. of limestone. If the difference of proportion determined by the chemical and field methods is a real one, as inspection of the data used seems to indicate, the significant questions are raised, (1) whether there may not be a concentration of limestones on continental areas, their complementary shales and muds being in the deep sea; or (2) whether limestone may not be concentrated in the upper, observed, part of the lithosphere, because of its known inability to remain in the deep-seated zones of high pressure and temperature. But whether the differences in results reached by the two methods are real or apparent, there is sufficient accordance in the main features of the redistribution of the elements for the purposes of the following discussion.

The changes summarized in the table are destructive or katamorphic (Van Hise) or descensional (Chamberlin and Salisbury). Chemically there is a sundering of complex silicates. The bases, for the most part, go off in solution and are precipitated as oxides, carbonates, sulphides, and even silicates, or remain in solution, a notable instance being sodium chloride. Kaolin develops simultaneously through the hydration in place of the remaining alumina silicates. Neither the free quartz nor other oxides are greatly changed. The mineralogical changes, so far as quantitatively known, may be roughly expressed by a comparison of the minerals of the average parent rock, and of the end-products in above proportion of sediments, as in the following diagram.

Feldspars obviously yield much the largest part of the shales, and a relatively small part comes from the ferromagnesian minerals. Quartz becomes more abundant in the katamorphosed rocks. The quartz of the sandstone may be regarded as corresponding in amount approximately with the free quartz of the igneous rock, indicating that the quartz of the shales is derived largely from the pre-existing feldspars. The minerals of the limestone and allied sediments are derived from the bases of the basic feldspars and ferromagnesian minerals.

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[1] W. J. Mead, "Redistribution of Elements in the Formation of Sedimentary Rocks," *Journal of Geology*, Vol. XV, No. 3, pp. 238 ff.

Physically, katamorphism of igneous rocks to average sediments means a slight increase in average volume of minerals of perhaps 3 per cent., a figure derived by comparing the specific gravities of the minerals of the parent rock with those of the resultant average sediments in the stated proportions. A similar result is obtained by calculating volume-changes from the chemical equations of the common alterations of the rock-making minerals to the minerals of the sediments. Where altered to extreme end-products throughout, such as kaolin, quartz, and calcite, there is an average volume-increase of minerals in due proportions, of about 18 per cent. Katamorphism

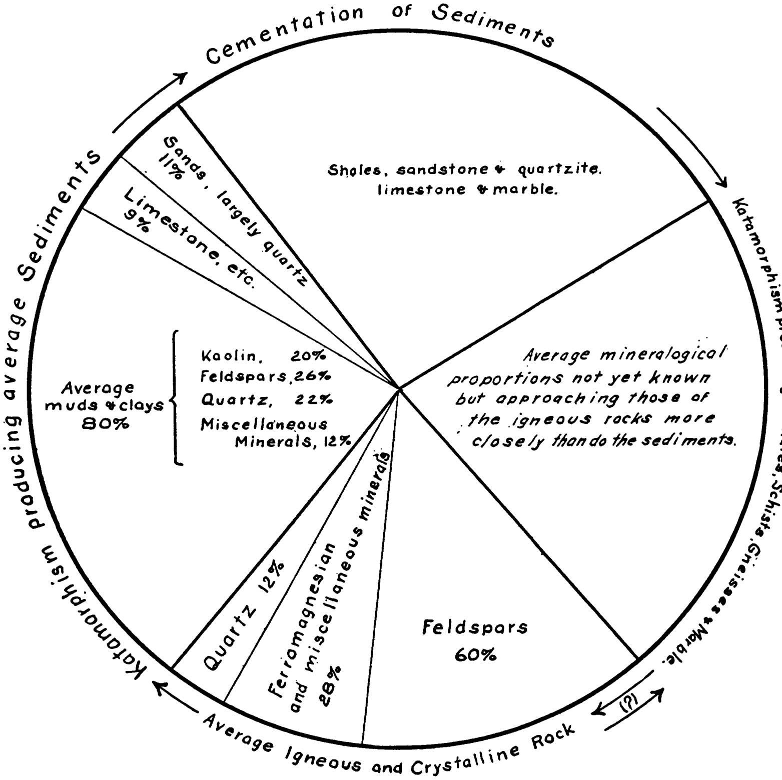
Cementation of Sediments
Shales, sandstone & quartzite, limestone & marble.
Sands, 11%, largely quartz
Limestone, etc. 9%
Average muds & clays 80%
Kaolin, 20%
Feldspars, 26%
Quartz, 22%
Miscellaneous Minerals, 12%
Average mineralogical proportions not yet known but approaching those of the igneous rocks more closely than do the sediments.
Katamorphism producing av. Slates, Schists, Gneisses & Marble.
(?)
Quartz 12%
Ferromagnesian and miscellaneous minerals 28%
Feldspars 60%
Average Igneous and Crystalline Rock
Katamorphism producing average Sediments

FIG. 1.—Diagram showing mineralogical redistribution in metamorphism.

means a greater volume-increase, by perhaps 40 per cent., when pore-space is figured, on the basis of experimental determinations of pore-space of the different classes of sediments, again combined in the stated proportions. There is still greater increase of volume if the substances remaining in solution, such as salts in the ocean, be calculated as solids. On the other hand, if only the residual materials from weathering are taken into account, not the chemical sediments, it may be shown that in spite of the increase in volume of certain minerals, the mineral volume of each of the principal rocks developed from the residual weathering materials has decreased. Volume-changes will be discussed in more detail in another article.

In general, katamorphism means simplification, both chemical and mineralogical, sorting, segregation of like substances, increase of volume, hydration, carbonation and oxidation—three processes usually involving liberation of heat. There is a net liberation or running-down of energy. Katamorphism is a great concentrating operation, with its maximum effect on igneous rocks, but also acting on sedimentary rocks so far as these contain minerals not already katamorphosed.

Ores, whatever their ultimate origin, while insignificant in bulk as compared with the sediments, illustrate well the net results of repeated concentrations, physical and chemical, under katamorphism. Whether we start with the ores as original magmatic segregations, or with ores resulting from igneous "after-action," or with ores derived directly from the katamorphism of igneous or sedimentary rocks, the ores become concentrated and segregated, and to a certain extent simplified, by katamorphism, and the richness and value of the metallic ore deposits are in a broad way proportional to the extent to which they have been katamorphosed. While some of the magmatic segregations may have value without katamorphism, it is certain that their value is increased by katamorphism. When we consider the iron ores, the lead and zinc ores of the Mississippi Valley, and the oxidized and enriched sulphide zones of copper and other vein and replacement ores, the economic importance of katamorphism in the ore-depositing processes is obvious. A classification of ores in terms of metamorphism is a suitable one for instructional purposes, in that it emphasizes the correlation or identity of ore-depositing and concentrating agencies with the common ones effecting the metamorphism of the lithosphere as a whole.

Stages in the partial redistribution of the elements above outlined appear in igneous rocks and in sedimentary rocks, so far as these have not become completely adapted to katamorphic conditions. Conglomerates, arkoses, and graywackes are largely in this class. Such partial changes are kaolinization, sericitization, and silicification of acid feldspars, or the alteration of basic feldspars by the development of epidote-zoisite, calcite, or prehnite and kaolin, or the change of augite to hornblende with separation of calcite, or of hornblende to chlorite and epidote with separation of quartz and iron oxide. In fact, most described "metamorphic" changes are of this partial kind, and the fact is frequently lost sight of that the completion of the observed alteration means ultimately the development of the simpler minerals of the sediments. It does not follow that the derivatives of the authigenic minerals of the igneous rocks are in each case less complex chemically than the original mineral. Epidote is as complex as feldspar, hornblende as augite. But the change is accompanied by the separation of other minerals that are less complex, such as kalin and calcite, and there is increase in volume when all end-products are taken into account, making the term "katamorphism" clearly applicable to the alteration. It may be emphasized that the long list of partial alterations of igneous rocks occurring in the upper part of the lithosphere are, with few exceptions, katamorphic in this sense, that they are usually accompanied by a separation of varying amounts of the end-products of alteration observed in sedimentary rocks. This phase of the subject will be discussed in another paper. With this clearly in mind, the study and understanding of the alterations of igneous rocks in upper zones become simplified.

In this connection, the question may be suggested: What are the broad differences between the metamorphism of surface volcanics and plutonic rocks, or between acid and basic rocks? It is not to be supposed that they alter equally in response to the demands of environment. Certain features of these differences are now known, but the subject has not yet been put on a systematic basis.

Cementation.—No sooner do the sediments, the end-products of katamorphism, reach their maximum incoherency, when the reverse, or reascensional process, is initiated, and they begin to strengthen themselves. Their pore-space becomes lessened under their own weight or that of superior beds, and solutions drop their load in the interstices; the rock becomes cemented. The tendency toward cementation seems by observation to be at its maximum at or just below the level of ground-water. Van Hise defines the belt of cementation as extending from the ground-water level to the lower limit of free movement of water; i. e., to the bottom of the zone of fracture. Cementation consists essentially of a consolidation and selective addition of materials in response to environmental demands for greater coherency. The principal chemical change is due to loss of water and to the proportions of cementing materials added. The resulting rocks are shales, sandstones, quartzites, and limestones, with the same kinds of minerals as in the unconsolidated sediments. The source and nature of the cementing materials may be summarized roughly by comparing the materials available in solution from the weathering of igneous rocks with the requirements of the sediments in the proportions above assumed. Observed percentage losses of elements—alumina being assumed constant, when averaged for cases of so-called "complete" weathering—show frequently about a 33 per cent. total loss of substances in solution when alumina is figured as constant. A hundred pounds of average igneous rocks therefore would contribute to solutions 33 pounds of material, of which 23 pounds is silica, 8 pounds calcium and magnesium carbonates, and the remainder soda, potassa, iron oxides, etc. This material is delivered partly through the overground circulation ultimately to the ocean, and partly to the underground circulation, where it becomes available for cementation. After taking out enough of the materials in solution to afford the ocean salts and the chemical and organic sediments in their known proportion to the total, the overwhelming dominance of silica is apparent in the materials left for cementing purposes. Calculations show that of the net amount of 23 pounds of material available for cementation in our average case, fully 20 pounds are silica. This is not out of accord with observed abundance of cements, when we take into account the mass of silica used in cementing shales, usually not considered. It is possible that, with liberal allowances for mechanical consolidation, the muds may still use more cementing material than other sediments combined.

Cementation also affects igneous rocks to the extent of filling fissures and other openings, but the process is insignificant in terms of the effect on the igneous rock itself, as compared with the effect on sediments.

Anamorphism.—When the cemented sedimentary rocks reach conditions of sufficient heat and differential pressure—which usually, though not always, means, when they reach the depth of rock-flowage—the reascensional, or constructive, development of the rocks continues under a set of processes which Van Hise has collectively designated as *anamorphic*. The minerals are recrystallized. Some of the simple mineralogical and chemical units become combined into relatively complex ones. The kaolin of shales becomes dehydrated, and this and other alumina silicates present are combined with the minor amounts of bases present to produce anhydrous silicates, which usually develop with a dimensional parallelism to meet the differential stress conditions, giving the rock a flow cleavage or schistosity. The quartz of the sandstones and quartzites combines with the minor amounts of clay and bases present to develop mica or other silicates—again usually, though not always, with parallel structure. The calcite of the limestone recrystallizes coarsely, usually without parallel structure, though sometimes possessing it; and there is a combination of the calcium with the small amounts of alumina silicates and bases which may be present, to develop pyroxenes, amphiboles, garnet, chloritoid, and other heavy anhydrous minerals. Chemically, the dominant processes are silication (and decarbonation) and dehydration, with a little deoxidation. The volume is reduced by closing pore-spaces, by the development of minerals with a higher average density (when taken in proportion of abundance), and, most important, by loss of materials. There is a tendency toward local mixing of substances, rather than segregation. Ores are modified, but not simplified and segregated. Adaptation to environment means, in short, the development of hard, dense crystalline slates, schists, and gneisses, some of the minerals of which approach more nearly in complexity those of the igneous rocks than do the minerals of the sediments.

Whether with more intense anamorphic conditions the sedimentary rocks actually pass into igneous rocks by subcrustal fusion or some analogous process, is yet a question which it is difficult to decide by direct observation, and which is partly a matter of definition. The burden of proof rests on those who hold that actual evidences of the change may be observed. It is easy to conceive that slightly assorted sediments containing essentially the minerals of the original igneous rocks may take on the characteristics of igneous rocks under these conditions; but, in proportion as the ultimate products of katamorphism have been developed and there is corresponding segregation of the simpler compounds, it is difficult to tell how these may again be brought together on any large scale to reproduce the proper mineralogical and chemical combinations of the igneous rocks. While silicates are developed, the main mass retains its simpler chemical characteristics and can be often distinguished from an igneous rock. If, as held by Van Hise, the processes of katamorphism and anamorphism both take place with a liberation or running-down of energy when both chemical and physical factors are considered, the completion of the metamorphic cycle on any broad scale seems doubtful.

It is further not clear whether the development of schists and gneisses from igneous rocks is predominantly katamorphic or anamorphic for the minerals of the igneous rock. In some observed cases the change is clearly katamorphic, such as the common development of hornblende from augite, of the alteration of a basic feldspar to a more acid feldspar with separation of clay and calcite, or the alteration of a potash feldspar to kaolin and sericite, although, as already indicated, one of the resulting minerals may be fully as complex as the original minerals. It is also equally certain that the observed development of heavy, anhydrous minerals, such as garnet, in the schistose igneous rocks means anamorphism.

The cycle.—The sequence of destructive and reconstructive changes above outlined constitutes a partial metamorphic cycle. If the slates, schists, or gneisses ever take on the characteristics of igneous rocks, through fusion and mixing, the cycle is complete. A necessary consequence of the cycle theory is that in the same zone changes may be both destructive and constructive—destructive to igneous and crystalline rocks, constructive to sedimentary rocks made up of end-products of katamorphism. It is true that the katamorphism of an igneous rock is most rapid and effective at the surface, while the cementation of the sediments occurs best at and immediately below ground-water level, and anamorphism of sediments begins only when the zone of rock-flowage has been reached. Thus there is a vertical succession of metamorphic zones, each with its own distinguishing characteristics; but in each of these are subordinate changes on opposite sides of the cycle. Katamorphism of an igneous rock near the surface is important, while, in the same zone, there is a minor amount of cementation of sedimentary rock. Cementation of sedimentary rock is important below ground-water level, where an igneous rock undergoes a relatively small amount of katamorphism. Anamorphism of certain sediments, especially

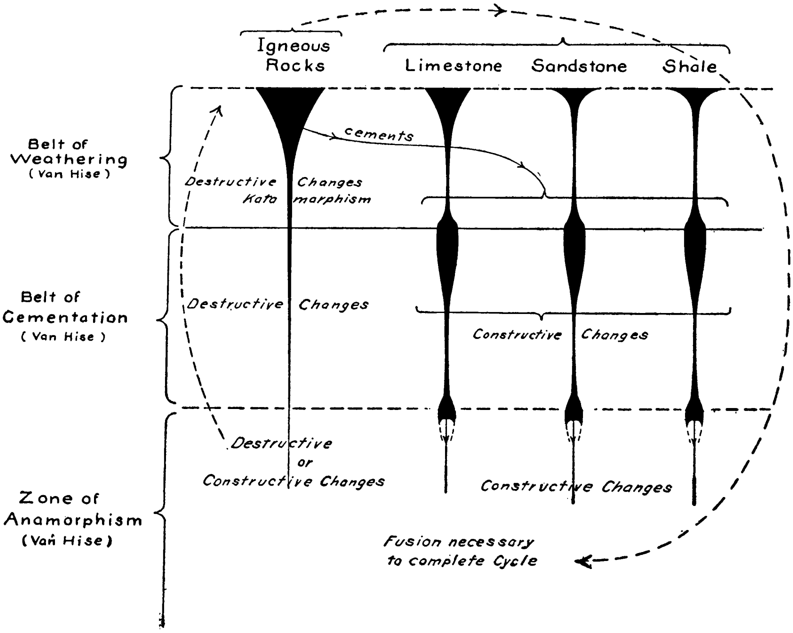
Igneous Rocks
Limestone
Sandstone
Shale
Belt of Weathering (Van Hise)
cements
Destructive Changes
Kato morphism
Belt of Cementation (Van Hise)
Destructive Changes
Constructive Changes
Zone of Anamorphism (Van Hise)
Destructive or Constructive Changes
Constructive Changes
Fusion necessary to complete Cycle

FIG. 2.—Sketch to show principal changes of principal rock in relation to zones of metamorphism. Thickened line indicates locus of maximum change. Horizontal lines indicating boundaries of zones are not corrected for thickness of zones or varying depth of zones for different rocks.

shales, may occur, while igneous rocks under the same conditions tend to katamorphism. In a highly idealized form the distribution of the changes with regard to zones, kinds of rocks, and kinds of changes, may be represented as in the figure on p. 312, in which the extent or importance of the change is represented in each case by thickness of line.

Van Hise states that the processes in each of the metamorphic zones may be reversed, thus in a way recognizing the cycle principle, but his full discussion emphasizes the dominant conditions and changes of the zones to such an extent that the student sometimes infers that all rocks in a given zone act alike. Grubenmann described three zones of schist-making—upper, middle, and lower—with the implication that all rocks suffer uniform changes in a given zone. Chamberlin and Salisbury imply the cycle idea in their use of the terms "descensional" and "reascensional" as applied to rock-changes, though the account of alterations and conditions is necessarily elementary. It is the purpose of the present paper to emphasize the necessity of the cycle theory in interpreting the zones of metamorphism. The "zonal" classification permits of necessary grouping of dominant phenomena, but confusion is likely to result unless the zones are considered in connection with particular rocks and alterations, and contrasting kinds of results for each zone are clearly discriminated.

Rôle of igneous rocks in metamorphic cycle.—The part taken in the metamorphic cycle by contact action of igneous rocks is most conspicuous in the anamorphic or constructive phases of the cycle, and may be regarded in general as furnishing higher temperature and pressure and hot solutions for the acceleration of anamorphism and for developing anamorphism in higher zones where the conditions are otherwise not anamorphic. Along the contacts are developed dense, complex, anhydrous silicates, such as garnet, staurolite, andalusite, amphibole, pyroxene, etc., and the rocks are recrystallized. Yet it is also true, especially near the surface, that the advent of igneous rocks brings about katamorphism in the adjacent rocks through the agencies of the hot waters and gases, magmatic, meteoric, or both, accompanying and following their introduction. In this class probably belong in part the prophylitic and allied alterations adjacent to ore-bearing veins in igneous rocks. The quantitative classification of igneous contact effects in terms of katamorphism and anamorphism has not yet been accomplished, or for that matter more than begun on any systematic scale. It is likely to yield interesting results. But whatever the specific relations of the influences of igneous rocks with conditions determined by depth they should require little essential revision of our conception of the metamorphic cycle for the reason that the cycle is based on a comparison of net results, and not on a comparison or weighting of the specific causes which have contributed to these results.

Classification of rocks.—The term "metamorphism" has in the past been largely applied to the development of slates, schists, and gneisses. This use of the term is implied in the prevalent textbook classification of rocks into igneous, sedimentary, and metamorphic divisions. The student comes to realize only with difficulty the fact that sedimentary rocks result from alteration of igneous rocks, just as do the so-called metamorphic rocks. Van Hise and others have included all rock alterations under metamorphism, and the same practice is observable in the descriptions of rock alterations by certain petrographers when they include under metamorphism many mineral changes which ultimately develop the sedimentary minerals. The development of the cycle idea further emphasizes the necessity of the broad use of the term "metamorphism," and the desirability of Van Hise's terms, "anamorphism" and "rock-flowage," to cover the schist-making changes formerly alone considered under metamorphism. With terms thus defined, the primary genetic classification of rocks becomes a dual one, *igneous* and *metamorphic*, the latter class being dually subdivided into the contrasting *sedimentary* and *schist-slate-gneiss* groups.